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Developments in large-scale coastal flood hazard mapping

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Abstract. Coastal flooding related to marine extreme events has severe socioeconomic impacts, and even though the latter are projected to increase under the changing climate, there is a clear deficit of information and predictive capacity related to coastal flood mapping. The present contribution reports on efforts towards a new methodology for mapping coastal flood hazard at European scale, combining (i) the contribution of waves to the total water level; (ii) improved inundation modeling; and (iii) an open, physics-based framework which can be constantly upgraded, whenever new and more accurate data become available. Four inundation approaches of gradually increasing complexity and computational costs were evaluated in terms of their applicability to large-scale coastal flooding mapping: static inundation (SM); a semi-dynamic method, considering the water volume discharge over the dykes (VD); the flood intensity index approach (Iw); and the model LISFLOOD-FP (LFP). A validation test performed against observed flood extents during the Xynthia storm event showed that SM and VD can lead to an overestimation of flood extents by 232 and 209 %, while Iw and LFP showed satisfactory predictive skill. Application at pan-European scale for the present-day 100-year event confirmed that static approaches can overestimate flood extents by 56 % compared to LFP; however, Iw can deliver results of reasonable accuracy in cases when reduced computational costs are a priority. Moreover, omitting the wave contribution in the extreme total water level (TWL) can result in a ~ 60 % underestimation of the flooded area. The present findings have implications for impact assessment studies, since combination of the estimated inundation maps with population exposure maps revealed differences in the estimated number of people affected within the 20–70 % range.

1 Introduction

During recent years, our societies have witnessed several extreme meteorological events which have raised public awareness of the fact that the climate is constantly changing and having a stronger footprint on everyday lives compared to previous decades. Given that a large part of the world's population lives near the coast, the ongoing sea level rise (SLR; DeConto and Pollard, 2016; IPCC, 2014) and its potential consequences have raised a lot of attention, initially among the scientific community, but also from the side of stakeholders, governments and the public.

There is a great number of recent studies which highlight that SLR will expose the coastal zone to greater risk in the years to follow (Hinkel et al., 2014; Losada et al., 2013; Weisse et al., 2014); while several others project that more frequent extreme weather events will enhance the impact of SLR on the coast (Brown et al., 2012; Debernard and Røed, 2008; Gaslikova et al., 2013; Lowe et al., 2009; Vousdoukas et al., 2016). During extreme events, the energetic atmospheric conditions result in transfer of mass and energy in the water element, which through the interaction with the bathymetry are manifested as increased water levels. When the latter coincide with spring tides, they can lead to extreme events, affecting landward areas which are normally protected by water (Barnard et al., 2015; Bertin et al., 2014).

The world's oceans are constantly exposing the coastal zone to energy fluxes, which are absorbed through dissipation and sediment transport processes, driving the coastal morphology to states, which are the most effective in attenuating ocean energy. During extreme conditions, most hydro-

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and morphodynamic processes are accelerated, with the most dramatic implication being the fact that the water level can exceed the height of natural (e.g., dunes, cliffs) or anthropic barriers (e.g., sea walls, dykes), and reach areas not prepared to interact with the water element, often with catastrophic consequences. This is the reason that marine storms are considered as extreme when they coincide with coastal inundation, and inundation maps are a crucial element for several coastal management and engineering practices, i.e., post-evaluation of extreme events, coastal planning, definition of set-back lines (Ferreira et al., 2006), and evaluation of adaptation options (Cooper and Pile, 2014; Hinkel et al., 2010).

The static inundation approach ("bath tub") considers all the areas with elevation lower than the forcing water level as flooded, comes with low computational costs and can easily be performed in GIS (geographic information system) environments (Seenath et al., 2016); for that reason it has been extensively used for studies of different scales (Hinkel et al., 2010, 2014; Vousdoukas et al., 2012c). However, given the high complexity of coastal flooding processes, several recent studies showed that the static approach results in substantial overestimation of the flood extent compared to dedicated hydraulic models, especially in flatter terrains (Breilh et al., 2013; Gallien, 2016; Ramirez et al., 2016; Seenath et al., 2016).

As intermediate solutions, approaches have been developed which are capable of reducing the computational cost by taking into consideration either only water mass conservation (Breilh et al., 2013), aspects of flooding hydrodynamics (Dottori et al., 2016) or the presence of obstacles (Perini et al., 2016; Sekovski et al., 2015). Dynamic, reduced complexity models like LISFLOOD-FP are a step more elaborate and more computationally intensive (Bates et al., 2010), which despite being originally developed for simulating river flow processes, have also been proven to be reliable for coastal flooding applications, such as the reproduction of storm surge events (Ramirez et al., 2016; Smith et al., 2012) and the evaluation of future scenarios of sea level rise (Purvis et al., 2008). At the same time, their application to large-/continental-scale (Alfieri et al., 2014) and global-scale river flood mapping efforts (Sampson et al., 2015) is also promising for their potential application to coastal flooding, but has not been explored yet. Finally, process-based models specialized for coastal hydro- and morphodynamics (Lesser et al., 2004; McCall et al., 2010; Roelvink et al., 2009; Vousdoukas et al., 2012b) would appear as the optimal option; however they come with the disadvantages of (i) the increased computational costs, which are almost prohibitive for large-scale application; and (ii) the fact that they require information about the nearshore topography in detail, which is often not available for many areas.

Despite the anticipated impacts of climate change along the world's coasts, there is a limited number of studies evaluating the risk of coastal inundation along the European coastline or worldwide, while existing ones are based on the static approach (Hinkel et al., 2010, 2014). Surprisingly, such large-scale studies neglect the contribution of waves to the extreme water levels, even though the latter has been shown to be important (Serafin and Ruggiero, 2014; Vousdoukas et al., 2012a). Against the foregoing background, the present study aims to propose a new methodology for mapping coastal flood hazard at European scale, by (i) considering the effect of waves when estimating extreme water levels; (ii) proposing the best method for coastal flood inundation mapping at continental scales, hereby trying to find a compromise between model complexity, data requirements vs. availability and constraints in computational power; and (iii) developing a framework which can be constantly upgraded every time new tools and data are available. To this end, four inundation approaches were tested and compared, initially on the grounds of their capacity to reproduce a historical extreme event. Subsequently, the four approaches are applied and evaluated at European scale, on the grounds of the estimated flood extents, but also in combination with socioeconomic information, in order to assess their effect on large-scale impact assessment of coastal flooding.

2 Data and methods

2.1 Total water level data

Extreme total water levels (TWLs) are the result of the contributions from the mean sea level (MSL), the tide and the combined effect of waves and storm surge ($\eta_{\text{W-SS}}$):

$$\text{TWL} = \eta_{\text{HTWL}} + \eta_{\text{W-SS}}(t), \tag{1}$$

where $\eta_{\text{W-SS}}$ becomes significant during extreme events, and η_{HTWL} is the high tide water level, defined as

$$\eta_{\text{HTWL}} = \text{MSL} + \eta_{\text{tide}}, \tag{2}$$

where MSL is the mean sea level, and η_{tide} is the tidal elevation. The above values were estimated at $\sim 11\,000$ points, equally distributed every 25 km along the European coastline.

Time series of tidal elevation (η_{tide}) were obtained from the TOPEX/POSEIDON Global Inverse Solution (Egbert and Erofeeva, 2002), and 10-year data were analyzed to obtain the maximum tide, given that the focus was extreme events. The TWL contribution due to extreme meteorological conditions $\eta_{\text{W-SS}}$ was reproduced by combining the effect of waves and storm surge.

- Time series of extreme storm surge levels (SSLs) were available from a storm surge hindcast run from 1 January 1979 to 1 June 2014 (Vousdoukas et al., 2016). The simulations were carried out forcing the Delft3D-Flow module of the open source model Delft3D (Deltares, 2014) by atmospheric pressure and wind fields obtained

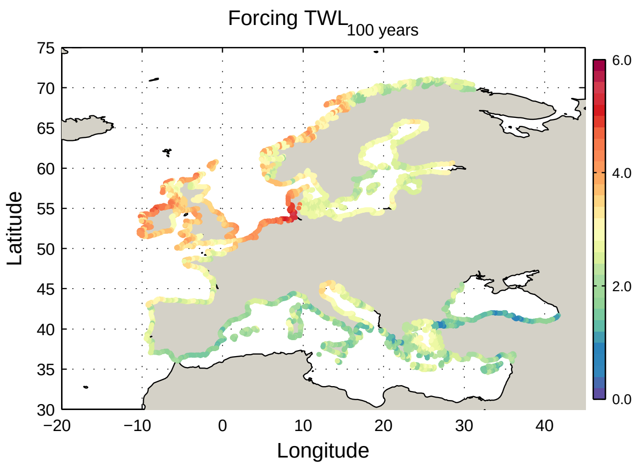

Figure 1. Total water level values for the present-day 100-year event along the European coastline; values are shown every 25 km of coastline.

from the ERA-Interim database (Dee et al., 2011). Detailed information can be found in Vousdoukas et al. (2016).

– Time series of significant wave height H_s were obtained by the ERA-INTERIM dataset (Dee et al., 2011).

The two datasets were combined to generate time series of the TWL component due to the combined effect of waves and storm surge according to the following equation:

$$\eta_{\text{W-SS}} = \text{SSL} + 0.2 \cdot H_s, \tag{3}$$

where $0.2H_s$ is considered to be a reliable approximation of the wave setup, i.e., the elevation in mean water level near the coast due to wave shoaling and breaking (US Army Corps of Engineers, 2002). More elaborate ways to estimate wave setup exist, also considering, apart from the significant wave height, the wave period and length and the beach slope. However, information about the nearshore bathymetry and/or the slope is not available at European scale, at the resolution required to resolve wave shoaling processes; therefore the solution was found to be the most reliable approach.

Subsequently, non-stationary extreme value statistical analysis (EVA) was applied to the 30-year $\eta_{\text{W-SS}}$ time series allowing the estimation of extreme $\eta_{\text{W-SS}}$ values for different return periods. The statistical analysis consisted in (i) transforming a non-stationary time series into a stationary one to which the stationary EVA theory can be applied, and (ii) reverse-transforming the result into a non-stationary extreme value distribution; this is described in detail in Mentaschi et al. (2016). The values presently considered correspond to the 100-year present-day event along the European coastline (Fig. 1).

The above implies that the pan-European application was simulating the hypothetical case that the 100-year event occurred simultaneously along the entire European coastline. The increase in sea level during an extreme event is episodic, and typically EVA only provides the TWLs, and no information about the temporal evolution of the event. This is a typical issue for similar studies and is usually dealt with the use of design hydrographs, such as the following one (Cialone and Amein, 1993):

$$\eta_{\text{W-SS}}(t) = \eta_{\text{peak}}\left(1 - e^{\left|\frac{D}{t}\right|}\right), \tag{4}$$

where $\eta_{\text{W-SS}}(t)$ is the time-varying water level above η_{HTWL} due to the combined effect of waves and storm surge, η_{peak} is the peak η_{extreme} (t) value, t the time and D the half duration of the event. The event duration was considered to be a function of η_{peak} according to a linear relationship estimated for each point, estimated from the following procedure: (i) the $\eta_{\text{W-SS}}$ water level time series was analyzed and extreme events were identified (on average five events per year); (ii) for each event the duration and peak water level were estimated; (iii) a best linear fit relationship between η_{peak} and D was estimated for each point and was applied in the subsequent stages of the analysis.

2.2 Inundation modeling

Four different inundation approaches were tested and are described from the most simplistic to the most elaborate and computationally intensive one:

– a static inundation method in which areas hydraulically connected with the sea and below TWLs are inundated (SM);

– a semi-dynamic method, where the water volume discharge over the dykes is computed based on time series of modeled water levels (VD), similar to the SO method described in Breihl et al. (2013);

– the flood intensity index approach (Iw) of Dottori et al. (2016), which reproduces flooding processes using an approximation of the water flow equations usually applied in two-dimensional (2-D) hydraulic models, considering the local topography, terrain roughness and basic information about the flood scenario;

– dynamic inundation modeling using LISFLOOD-ACC (LFP; Bates et al., 2010; Neal et al., 2011), a 2-D hydraulic model which is part of the LISFLOOD-FP model (Bates and De Roo, 2000); LISFLOOD-ACC has a 1-D inertial model (e.g., advection is not considered) where x and y directions are decoupled in 2-D simulations over a raster grid; recent work by Neal et al. (2011) showed that LISFLOOD-ACC is a faster alternative to full shallow-water models for gradually varied subcritical flows, providing results of similar accuracy as those of more complex models, both in terms of flow velocity and water depths, with a considerably reduced computational effort.

Given that the spatial extent of the study area did not allow running simulations for the entire domain, the European coastline was separated into ∼ 11 000 segments, each covering 25 km of shoreline and extending 100 km landward. Elevation data for the flood simulations were taken from SRTM DTM at 3 arcsec (∼ 90 m) resolution. For simulations with the LFP and the Iw approach, hydraulic roughness values were derived from the CORINE Land Cover map (Batista e Silva et al., 2012), as in Alfieri et al. (2014).

After the application of each approach, the flooded area (FA) was estimated in square kilometers, while values were also aggregated in country level, and normalized by country shoreline length, available from the World Resources Institute (www.wri.org). In addition, FA values were grouped according to the geological characteristics of the coastline, available from the European Environmental Agency (www.eea.eu). The dataset originally includes 20 geological coastline classes, some of which were merged in order to reduce the total number to 12, with the mean FA estimated for each shoreline class. Finally, the effect of the inundation approach on potential estimated number of people affected by coastal flooding was assessed by combining the generated inundation maps with population maps at 100 m resolution for Europe (Batista e Silva et al., 2013). The number of people affected was considered to be equal to the total number of people located in areas predicted to be flooded.

2.3 Integration of coastal protection structures

Sufficient digital elevation model (DEM) resolution is crucial for inundation modeling, and ideally < 10 m resolution lidar data are recommended for reliable results (Vousdoukas et al., 2012b, c). However, such datasets are often not available for continental-scale studies, though such resolution implies computational costs which are usually prohibitive. The 100 m resolution DEM presently used was a compromise between sufficient resolution and computational effort, but was not sufficiently fine to resolve coastal protection structures, implying a potential overestimation of inundation extents.

The lack of detailed information about flood protection structures at European scale is a known issue (Scussolini et al., 2016), and all available data on coastal protection in Europe have been compiled from open databases and national authorities (www.ahn.nl; UK Environmental Agency, personal communication; Vafeidis et al., 2008). It is a fact that not all countries provide such spatial maps with resolution fine enough for the analysis taking place in the present study. Therefore, the dataset was completed with information obtained through personal communication with national authorities and the coastal engineering community, in order to cover the more important areas, e.g., the cities. For areas along the coast for which no information was available, an arbitrary minimum protection standard was assumed, depending on the population density, i.e., equivalent to the 5-year and the 10-year event for population density lower and higher than 500 people km^{-2}, respectively. The TWL for the corresponding return period was estimated from the extreme value analysis and was considered as elevation of the coastal protection (Fig. 2). Finally, the protection information was introduced in the DEM by assigning the height of the coastal protection as elevation of all the DEM cells found on the coastline and having elevation lower than the one of the protection (Fig. 2).

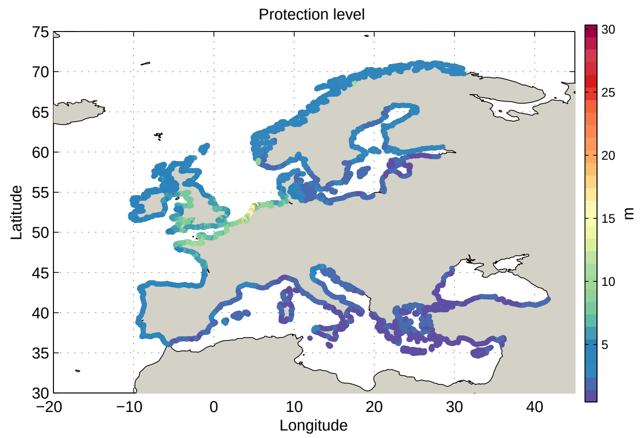

Figure 2. Protection standards considered along the European coastline, expressed as design total water levels (TWLs).

2.4 Model validation

Model validation requires measurements from historical flooding events and in particular, a combination of water level time series and flood extent maps for the same event. In general, there is scarcity of well-documented coastal inundation events, and according to our knowledge, the Xynthia storm was the only recent, large-scale event which was sufficiently documented in Europe. Xynthia hit the Atlantic coast of France in February 2010, causing the flooding of large coastal areas, with 47 deaths and at least EUR 1.2 billion of damage (CGEDD, 2010). The coastal area located northward of the Gironde estuary was the most severely affected, where flooded areas detected from satellites exceeded 300 km^2 and extensive information is available from reports and scientific literature (Bertin et al., 2012, 2014; Breilh et al., 2013).

The coastline in the most flooded area is irregular and characterized by generally shallow sea floor area and large embayments, with extensive intertidal mudflats and coastal marshes. To prevent frequent marine flooding of these low-lying wetlands, an extensive system of dykes, levees and locks has been built over the last centuries, with an average height reported to be around 6 m. The elevation of the dykes was included in the DEM; however several dyke failures occurred during the event (Breilh et al., 2013) that have not been considered in the simulations, since their timing and location are unknown. Storm surge water levels were taken from observed water level at the La Pallice tide gauge, while

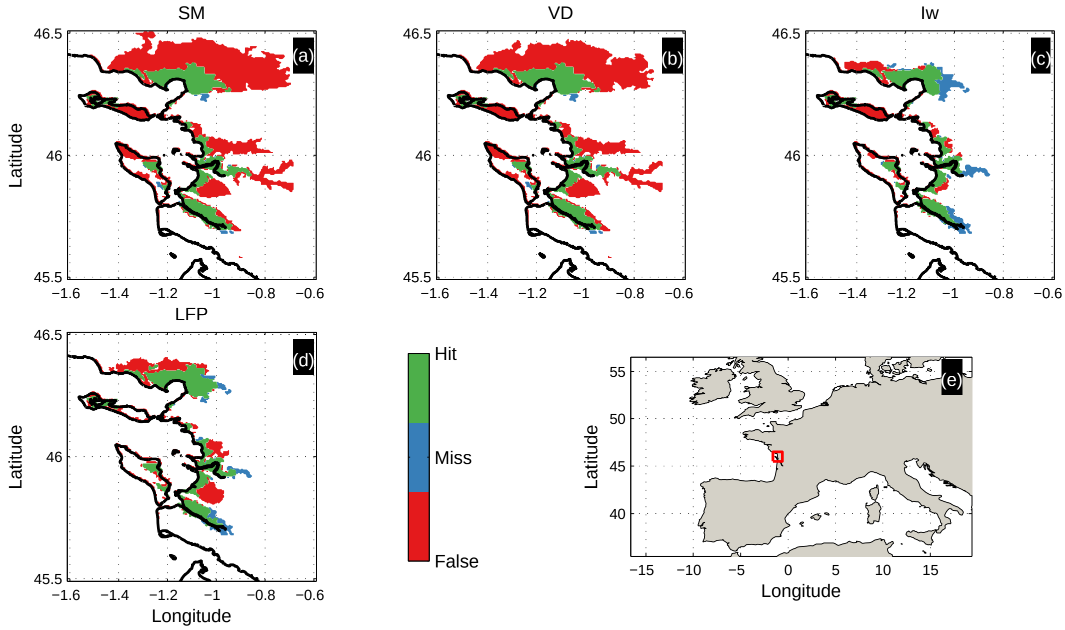

Figure 3. Validation of the LISFLOOD-FP model for the Xynthia storm: maps showing the comparison of the simulated and observed flood extent, as well as their intersection: green, blue and red colors correspond to inundated areas predicted, not predicted and overpredicted by the model, respectively. Map **(e)** shows the location of the study area.

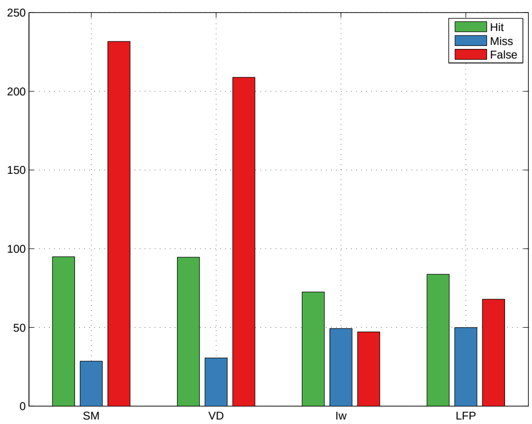

Figure 4. Validation of the different inundation approaches (bar bundles) for the Xynthia storm, on the grounds of the H, F and C rates (shown by different colors).

flood extent was available from field measurements (Breilh et al., 2013; DDTM-17, 2011). River discharge has not been considered in the simulation, as the flooding event appeared to be mainly driven by high sea water levels.

The skill of the inundation approaches to reproduce the inundation events was evaluated on the grounds of agreement between simulated and observed flood footprints. Three different skill indexes were used, commonly applied for fluvial flooding (Alfieri et al., 2014; Bates and De Roo, 2000). The hit ratio H is a proxy of agreement between simulated and observed inundation maps and it is defined as

$$H = \frac{\mathrm{Fm} \cap \mathrm{Fo}}{\mathrm{Fo}} \times 100, \tag{5}$$

where $\mathrm{Fm} \cap \mathrm{Fo}$ is the area correctly predicted as flooded by the model, and Fo indicates the total observed flooded area. Since the hit ratio does not take into account over-prediction, the false alarm ratio F was also considered, defined as

$$F = \frac{\mathrm{Fm} / \mathrm{Fo}}{\mathrm{Fo}} \times 100, \tag{6}$$

where $\mathrm{Fm} / \mathrm{Fo}$ is the area wrongly predicted as flooded by the model. Finally, a more comprehensive measure of the agreement between simulations and observations is given by the critical success index C, defined as

$$C = \frac{\mathrm{Fm} \cap \mathrm{Fo}}{\mathrm{Fm} \cup \mathrm{Fo}} \times 100, \tag{7}$$

where $\mathrm{Fm} \cup \mathrm{Fo}$ is the union of observed and simulated flooded areas.

3 Results

3.1 Validation for the case of the Xynthia storm

The comparison of the observed inundation maps with the ones estimated by the different approaches showed that the static approach largely overestimates the flood extent

Table 1. Values of flooded area per European country for the present-day 100-year event (in km^2), obtained from the four tested inundation approaches. Totals for Europe and EU28 are also provided.

	SM	VD	IW	LFP
Belgium	0.0	0.0	0.0	0.0
Bulgaria	148.1	159.2	73.5	70.1
Cyprus	100.3	117.6	92.9	69.5
Germany	5401.8	1485.8	3615.6	3051.0
Denmark	4243.0	3077.4	3116.4	3201.1
Estonia	328.0	547.6	318.1	312.8
Spain	611.8	606.5	544.5	447.1
Finland	405.5	616.9	366.0	356.4
France	3202.6	996.9	1884.4	980.8
Greece	2547.6	2877.0	2013.0	1924.7
Croatia	621.1	1090.1	613.8	607.4
Ireland	1712.9	2876.5	1590.9	1649.3
Italy	5582.0	2428.3	2470.4	1916.3
Lithuania	1129.3	521.2	528.4	543.6
Latvia	127.1	161.9	103.7	92.3
Malta	10.9	15.7	10.9	7.2
Netherlands	71.9	0.4	68.4	3.4
Norway	4936.6	8369.4	4967.5	4843.3
Poland	1689.6	1252.7	782.3	861.9
Portugal	343.8	200.9	251.1	171.0
Romania	4408.7	2080.7	1314.5	1664.4
Sweden	1519.8	1989.3	1401.6	1269.1
Slovenia	24.9	44.6	21.9	23.2
Turkey	1375.0	1725.0	868.9	877.8
United Kingdom	9910.5	5371.5	5491.8	5752.9
EU28	44 141.1	28 518.6	26 674.2	24 975.5
EU total	50 452.6	38 613.0	32 510.6	30 696.6

(Fig. 3a), while taking into consideration the volume of water passing above the dykes (VD) improves the performance marginally (Fig. 3b). Therefore, even though the hit rate for SM and VD was $H > 95\,\%$, F rates were higher than 200 % and C rates around 25 % (Fig. 4). On the other hand the Iw and LFP approaches resulted in realistic flood extents, with the latter performing slightly better (Fig. 3c–d). LFP resulted in higher Hit rates than Iw (73 and 84 %, respectively), but also higher overestimation of the flood extents compared to Iw (F rates 47 and 68 %, respectively). The two methods produced comparable results, with C rates being slightly better for LFP compared to Iw (49 and 50 %, respectively).

3.2 Coastal flooding hazard assessment at European scale

All four coastal inundation approaches were applied for the 11 124 coastal segments along the European coastline in order to estimate flood extents (Fig. 5), which were then aggregated at country level (Fig. 6 and Table 1). The static approach resulted in the highest total FA (FA $\approx$ 50 381 km^2 for Europe), showing values substantially higher than the other approaches, especially along areas of the coast which are known for their low-lying/mild-slope terrains (e.g., North Sea; Fig. 5a). The total flood extent for Europe based on VD

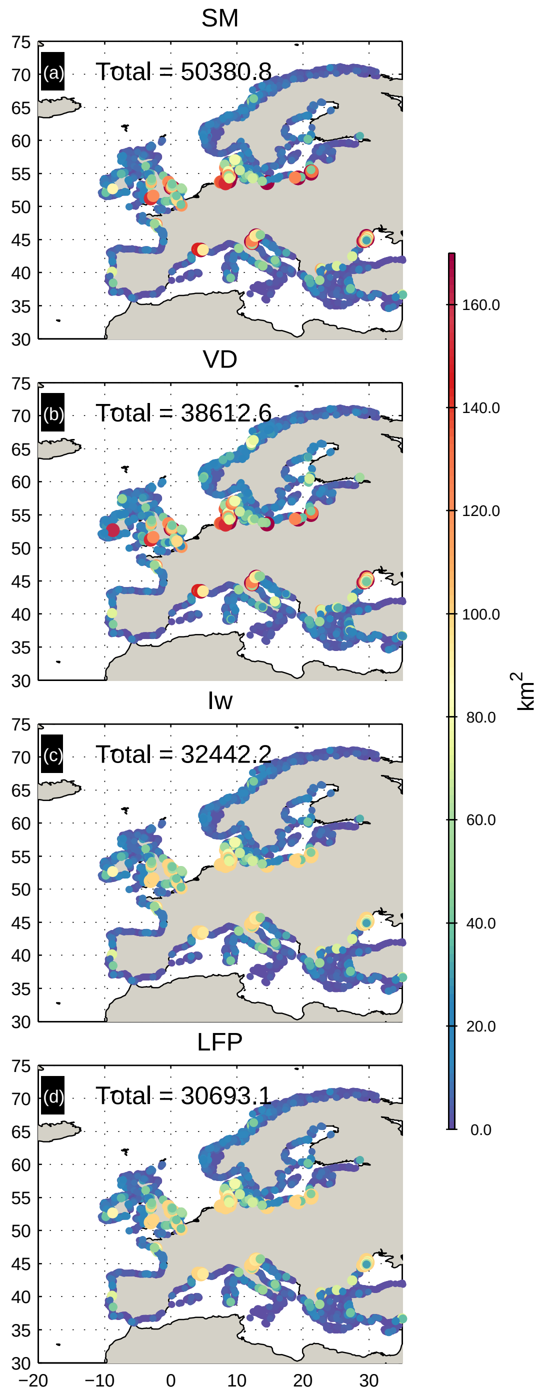

Figure 5. Estimated coastal flood extent for the present-day 100-year event using all four approaches. Values are shown for each 25 km coastal segment and correspond to km^2.

was FA $\approx$ 38 613 km^2, slightly higher than the one for Iw (FA $\approx$ 32 510 km^2, Fig. 5b–c), while LFP resulted in the lowest total flood extent overall, with FA $\approx$ 30 696 km^2 (Fig. 5d). The spatial FA variations obtained from LFP and Iw were similar, in contrast to VD and SH, the results of which were characterized by some values which were substantially higher than the European mean.

3.3 Results per country and coastline type

Aggregating the FA values per country and normalizing per shoreline length showed that LFP and Iw resulted in relatively similar values (Fig. 6c–d), with the exception of slightly higher Iw values for Germany and LFP values for Romania. The static approach resulted in higher FA per shoreline length, especially for Germany, Poland, UK and Italy (Fig. 6a). Values from VD varied overall within the ones of LFP and SM, with the exception of Germany for which the FA estimated from VD was the lowest among all approaches tested. Romania and Lithuania were the countries resulting in the higher FA per shoreline length in Europe.

Aggregating the FA values per coastline type showed that SM resulted in values higher than the other approaches by more than 30 %, for all but three classes for which the differences were smaller: soft strands, artificial beach and small beaches (Fig. 7). Similar to the previous findings, values from VD were higher than the ones of VD and LFP with the exception of three classes, for which VD produced the lowest values: artificial protection, embankments and muddy sediments. Differences between LFP and Iw were small, with the former resulting in slightly higher FA for all classes apart from vegetative strands.

3.4 Implications for coastal management and adaptation studies

Inundation maps are typically combined with socioeconomic exposure maps to assess coastal impacts or planning scenarios (Alfieri et al., 2015, 2016; Boettle et al., 2016; Prahl et al., 2015). Given that the number of people affected (NPA) is a parameter commonly considered and even used as a direct or indirect proxy of coastal impacts (Brown et al., 2013; Hinkel et al., 2010; Lloyd et al., 2015), the sensitivity of the estimated total NPA to the applied inundation approach was assessed. At this stage only SM and LFP were considered for reasons of simplicity, SM as the most common approach found in the literature, resulting in the higher flood extents (Fig. 5a), and LFP being on the other extreme, producing the lowest FA values (Fig. 5d) and being the most physically sound and complex approach to implement, among the ones tested.

SM resulted in 56 % higher FA values than LFP for the whole of Europe, translated to a 65 % increase in the NPA (∼ 5 million instead of ∼ 3; Fi. 8). Not all countries showed the same sensitivity to the inundation approach used; e.g., relative differences in estimated FA from the two approaches reached, or even exceeded 50 % for France, Italy, Romania, Portugal, Lithuania and the UK, but were < 25 % for the other countries. The above differences were also "transferred" into NPA differences, but not in a linear way. The combination

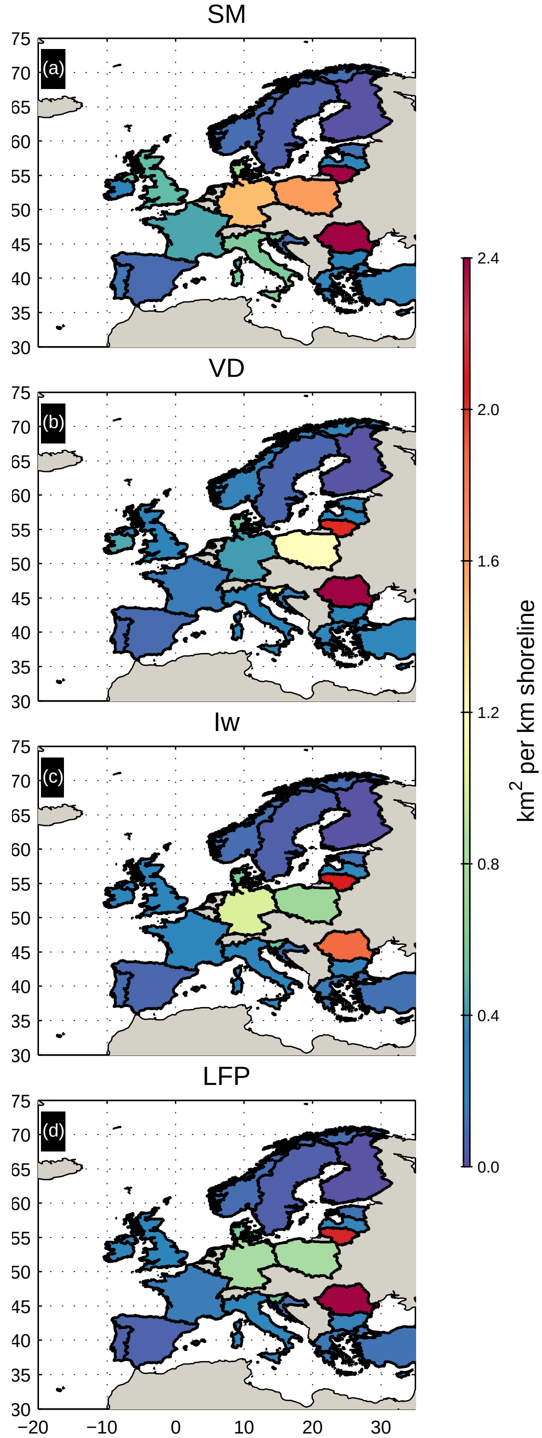

Figure 6. Estimated coastal flood extent for the present-day 100-year event using all four approaches, aggregated per country level, and normalized by coastline length. Values correspond to km^2 per km of coastline.

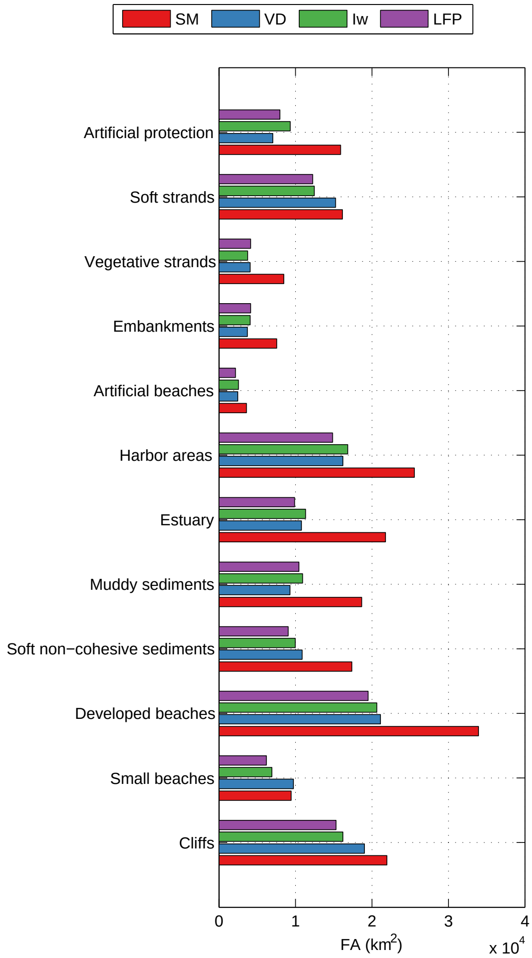

Figure 7. Comparison of the flooded area (FA) for the present-day 100-year event aggregated per coastline type for all four inundation approaches. Values correspond to km^2 per km; colors express the different inundation approaches (see legend) and horizontal bar stacks denote the shoreline type.

with the population maps resulted in higher NPA differences for Germany, Poland and Denmark, compared to the ones for FA, while relative NPA differences for France and Italy were reduced.

Including the wave contribution in the TWL estimation resulted in a $\sim 150\,\%$ increase in FA for the whole of Europe, with the relative FA differences exceeding 50 %, with the exception of few countries like Estonia, Greece, Croatia, Lithuania, Romania and Turkey (Fig. 9a). The increase in the European total NPA after including the wave effect was even higher, around 167 % (~ 3.2 vs. 1.2 million; Fig. 9). The relative difference was higher than for FA for several countries, such as Germany, Denmark, Ireland, Latvia, Norway and the UK (Fig. 9b). Considering the wave effect was also shown to change the relative contribution of some countries to the European total, both for FA and NPA. For example UK, Norway, Germany and Denmark were shown to contribute more to the total once the waves were included in the analysis (Fig. 9).

4 Discussion

4.1 Evaluation of inundation approaches

Validation of the static approach for the Xynthia storm showed that it results in severe overestimation of the flood extents in agreement with the findings of previous studies (Bertin et al., 2014; Gallien, 2016; Ramirez et al., 2016). The Iw and LFP approaches showed satisfactory predictive skill, which is an important finding since they were applied for Xynthia with the same setup as they were implemented for the entire European coastline, confirming the validity of the approach for large-scale application.

Breihl et al. (2013) applied three different inundation approaches to simulate the Xynthia storm: (i) a static inundation approach forced by the maximum sea level recorded during the storm at La Pallice tide gauge (SM1); (ii) a second static approach which considers the space-varying maximum sea levels simulated by a storm surge modeling system (SM2); and (iii) the semi-dynamic VD method (VD-B2013). Their results are quantitatively similar even though they cannot be directly comparable with the present ones, since Breihl et al. (2013) used a higher resolution DEM based on lidar data, which can take coastal defenses and sedimentary barriers into account, enhancing model performance and allowing a more detailed analysis. Comparisons are more straightforward with results from Ramirez et al. (2016), who obtained similar C values running CAESAR-LISFLOOD on a Shuttle Radar Topography Misison (STRM) 90 m DEM, also concluding that the static approach can overestimate FA by $\sim 200\,\%$.

Dyke failure events were reported during Xynthia, and since they were not taken into consideration in the simulations, they could be responsible for the weaker predictive skill in some areas. The latter could be partially compensated by considering morphodynamic evolution during the inundation events; however such modeling is very computationally expensive and thus not feasible at large scales, also due to the lack of essential data for such simulations (e.g., about sediment characteristics). Overall, the results from the simulation of the Xynthia storm using Iw and LFP show that the latter can produce reliable results, even when applied to a lower resolution DTM, which is an inevitable compromise for large-scale applications, given the currently available computational power and data.

4.2 Towards an improved approach for pan-European coastal flood hazard mapping

The methodology for coastal inundation assessment presently proposed is improved in several aspects compared to the current state of the art in large-scale coastal flood

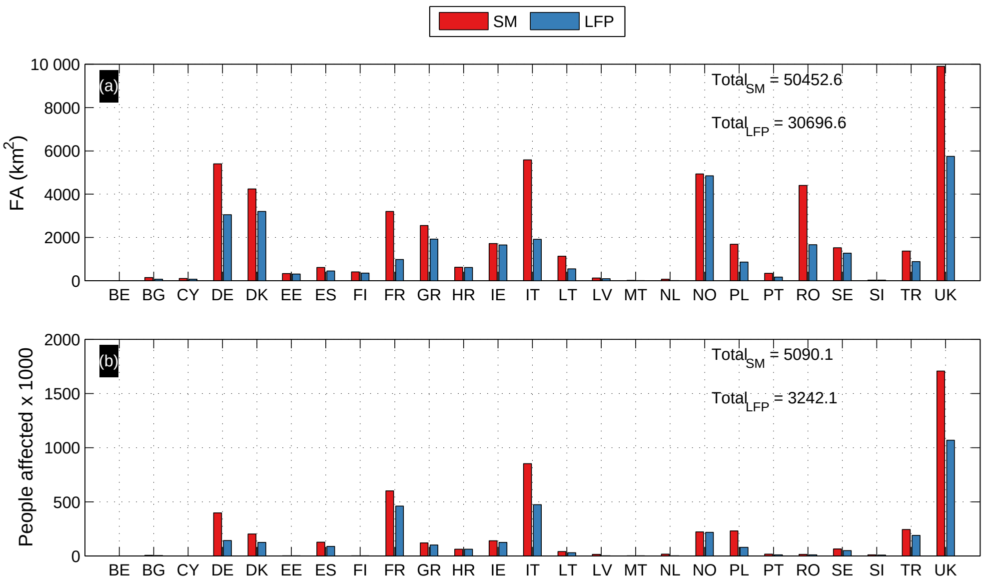

Figure 8. Estimated values of the country level FA **(a)** and thousands of people affected **(b)** for the present-day 100-year event; comparisons between the results using the static approach and LISFLOOD-FP.

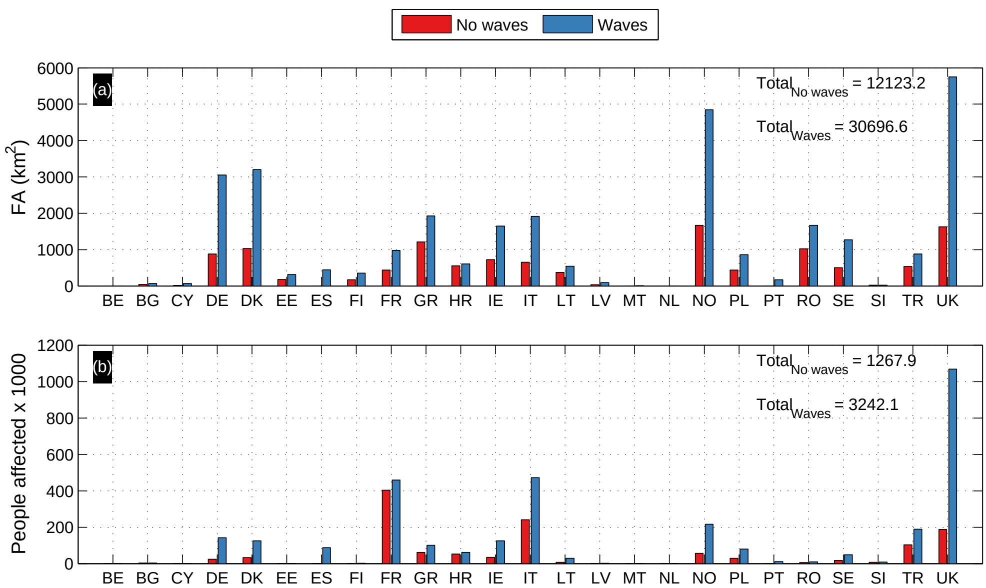

Figure 9. Estimated values of the country level FA **(a)** and thousands of people affected **(b)** for the present-day 100-year event; comparisons between the results considering TWLs including/excluding waves.

hazard mapping. Waves lead to an additional elevation in mean water level near the coast due to wave shoaling and breaking, which during extreme events can be significant, especially for exposed coastlines like the ones found along the Atlantic coast of Europe (Ciavola et al., 2011; Losada et al., 2013; Serafin and Ruggiero, 2014). Nevertheless wave contribution is often neglected by existing large-scale studies and present results underline that omitting the wave effect can affect both the estimated FA and any consequent impact calculations.

Moreover, few studies exist which assess coastal inundation at European scale, and overall, previous continental-/global-scale efforts have been based on the static inundation approach (Hinkel et al., 2010, 2014), which has been shown to overestimate FA (see present findings, but also Bertin et al., 2014; Gallien, 2016; Ramirez et al., 2016). As an improvement, the pan-European application shows that large-scale application of LFP is feasible; the computational effort still implies the availability of a computational facility. When the latter is not available, Iw can be considered to be a valid alternative, as it was shown to produce comparable results with computational times an order of magnitude lower.

The estimations of the number of people affected, based on the produced inundation maps discussed in Sect. 3.4, highlight that the increased complexity and computational effort related to the migration from the static to dynamic inundation approaches can be outbalanced by the benefits in the quality of the produced results. High-quality/detailed inundation maps are critical for coastal studies since the density of valuable assets often tends to increase landward near the coast. The section stretching along the first hundreds of meters near the sea acts as a buffer absorbing energy from the ocean, and is typically too dynamic to host critical infrastructure. However, landward of that area, the density of population and valuable assets is typically high. Therefore, overestimating flood extents is likely to result in a disproportional increase in estimated impacts. The static approach was shown to result in overestimated flood extents for the coastline classes of artificial protection, harbor areas, developed beaches and embankments, which imply increased socioeconomic activity and high impact in the case of flooding.

Ramirez et al. (2016) found that the static approach produced comparable results with CAESAR-LISFLOOD for Hurricane Sandy, a potential effect of the steep landscape. The latter was confirmed by the present findings reporting smaller deviations between SH and the other approaches, for coastline classes typically associated with steep terrains (i.e., cliffs, artificial beaches and small beaches; see Fig. 7). In contrast, higher deviations were observed for classes associated with mildly sloping landscapes, i.e., estuary, muddy sediments and vegetative strands.

A surprising finding in the comparison of the results from the pan-European application with the ones for the Xynthia storm was that while VD largely overestimated Xynthia FA, it produced results which were higher but comparable to the ones from Iw and LFP for Europe. The reason could be that VD is sensitive to the protection standards considered, as the height of the dykes controls the volume of water active in the inundation and consequently the flood extent. The latter can be discerned by (i) the fact that estimated FA along the better protected North Sea coastline from VD is lower than from Iw, while the opposite is the case for several less protected Mediterranean locations (Fig. 5); and (ii) the fact that the VD produced the lowest FA values among all the methods for the coastline class Artificial protection (see Fig. 7), which was typically not the case for other coastline types.

Potential improvements in the methodology could include (i) considering the contribution of wave run-up to the TWLs (Perini et al., 2016; Serafin and Ruggiero, 2014); (ii) applying a multivariate approach for the extreme value statistics (Corbella and Stretch, 2013; Gouldby et al., 2014; Hawkes et al., 2002); and (iii) taking into account all the wave-related processes contributing to coastal flooding (i.e., erosion, overwash and breaching; e.g., Matias et al., 2008; McCall et al., 2010). The latter implies simulating a spectrum of hydro- and morphodynamic processes, and such application at European scale would be challenging, given the IT resources as well as the high-resolution data required.

Even without considering the wave-driven morphological change during extreme events, swash processes result in an additional contribution to the TWLs through wave run-up (Stockdon et al., 2006; Vousdoukas, 2014; Vousdoukas et al., 2012c). Despite its importance, wave run-up was not included in the present analysis since (i) its estimation requires the beach-face slope as input, information which is missing for most of the European coastline; (ii) swash-related water level fluctuations typically have periods of seconds, and thus take place at smaller temporal scales than the other TWL components. Therefore, the authors are confident that the present approach is sound, especially considering that the aim is to simulate coastal flooding during very rare, extreme events.

The approach to combine the effect of waves, tides and storm surges has been referred to as the structure-variable method (SVM; see Bruun and Tawn, 1998), who also proposed alternative multivariate approaches. The latter can take into account the fact that the impact of an extreme meteorological event can depend on whether it coincided with spring tide (Bertin et al., 2012; Vousdoukas, 2012). While there is no doubt that multivariate approaches are more appropriate for engineering purposes, SVM was considered as sufficient since (i) the TWL was the only input required for the present modeling efforts; (ii) the way to combine the different TWL components is only one of the many sources of uncertainty for such large-scale studies and probably less significant compared to inaccuracies in the DEM and the protection standards, among others; (iii) one of the main motivations of the present work is to develop a methodology allowing impacts of coastal flooding to be assessed in terms of climate change, and for that reason the emphasis was put on developing a non-stationary statistical approach. Ongoing work includes several improvements of the current methodology, including the above aspects.

The quality of the information about coastal flood protection is critical for studies like the present one, and it is a known issue that such data are not available along the entire European coastline at the resolution desired for the inundation modeling. This has also been highlighted by previous studies on river flooding (Scussolini et al., 2015). One potential solution would be to carry out reverse calculations of protection based on expected flood extents or impacts, but this is still a challenge, given that such information is generally not available. However, it is important to stress that the goal of the present contribution is to establish a general framework for the assessment of flooding issues at the European level, based on process-based models and dynamic simulations. Both of these aspects are very novel in these types of studies. The proposed framework allows for constant improvement of the quality of the results whenever new and more accurate data become available.

5 Conclusions

A new methodology for mapping coastal flood hazard at European scale was presented, combining (i) the contribution of waves to the total water level; (ii) improved inundation modeling; and (iii) an open, physics-based framework which can be constantly upgraded whenever new and more accurate data become available.

Four inundation approaches of gradually increasing complexity and computational costs were evaluated in terms of their applicability to coastal flooding mapping along the European coastline: static inundation (SM); a semi-dynamic method, considering the water volume discharge over the dykes (VD); the flood intensity index approach (Iw); and the model LISFLOOD-FP (LFP). To the best of our knowledge, this is the first attempt to produce coastal flood hazard estimations at continental scale using dynamic flood mapping approaches.

A validation test was performed against observed flood extents during the Xynthia storm event that occurred in 2010 in France. The results showed that SM and VD can lead to an overestimation of flood extents by 232 and 209 %, respectively, while Iw and LFP showed satisfactory predictive skill, especially considering that the setup was designed for large-scale application, using a coarse 100 m DEM.

Application at pan-European scale for the present-day 100-year event confirmed that (i) static approaches can overestimate flood extents by 56 % compared to LFP, and that (ii) the latter can be applied successfully for large-scale studies. However, Iw can deliver results of reasonable accuracy in cases when reduced computational costs are a priority.

The results showed that omitting the wave contribution in the extreme TWLs can result in a ~ 60 % underestimation of the flooded area. Moreover, considering the wave contribution to the TWLs changed the relative contribution of some countries to the European total, due to the fact that for a part of the European coastline, waves are a more important hazard component compared to storm surges.

The present findings have implications on impact assessment studies, since the combination of the estimated inundation maps with population exposure maps showed differences in the estimated number of people affected within the 20–70 % range.

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